A preliminary overview of the multiconjugate adaptive optics module for the E-ELT

Emiliano Diolaiti[*a], Jean-Marc Conan[b], Italo Foppiani[c], Matteo Lombini[a], Cyril Petit[b], Clélia Robert[b], Laura Schreiber[c], Paolo Ciliegi[a], Enrico Marchetti[d], Michele Bellazzini[a], Lorenzo Busoni[e], Simone Esposito[e], Thierry Fusco[b], Norbert Hubin[d], Fernando Quiros-Pacheco[e], Andrea Baruffolo[f], Sandro D'Odorico[d], Jacopo Farinato[f], Benoit Neichel[b], Roberto Ragazzoni[f], Carmelo Arcidiacono[f], Valdemaro Biliotti[e], Giovanni Bregoli[a], Giuseppe Cosentino[c], Giancarlo Innocenti[a]

[a]INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy;
[b]ONERA, DOTA-CC, 29 av. de la div. Leclerc, BP 72, 92322 Chatillon cedex, France;
[c]Università di Bologna – Dipartimento di Astronomia, via Ranzani 1, 40127 Bologna, Italy;
[d]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching b. Muenchen, Germany;
[e]INAF – Osservatorio Astrofisico di Arcetri, largo E. Fermi 5, 50125 Firenze, Italy;
[f]INAF – Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, 35122 Padova, Italy;

ABSTRACT

The multi-conjugate adaptive optics module for the European Extremely Large Telescope has to provide a corrected field of medium to large size (up to 2 arcmin), over the baseline wavelength range 0.8-2.4 µm. The current design is characterized by two post-focal deformable mirrors, that complement the correction provided by the adaptive telescope; the wavefront sensing is performed by means of a high-order multiple laser guide star wavefront sensor and by a low-order natural guide star wavefront sensor. The present status of a two years study for the advanced conceptual design of this module is reported.

Keywords: Extremely Large Telescopes, E-ELT, multi-conjugate adaptive optics, laser guide stars, sky coverage

1. INTRODUCTION

The Multi-conjugate Adaptive Optics RelaY (MAORY) is one of the post-focal adaptive optics modules currently under study for the European Extremely Large Telescope[1]. MAORY has to provide a corrected Field of View (FoV) of medium (20''-1') to large size (up to 2'), over the baseline wavelength range 0.8-2.4 µm. The correction over the medium field is expected to be of high quality, in terms of Point Spread Function (PSF) quality and uniformity, the detailed performance depending on the actual field diameter and on the observing wavelength; the large field is characterized by a lower level of correction quality and uniformity. MAORY shall feed different instruments, among which a high angular resolution imaging camera and probably a spectrograph.

The current baseline concept is based on the use of Laser Guide Stars (LGS), following the choice adopted in other Multi-Conjugate Adaptive Optics (MCAO) systems, both for present telescopes (e.g. the MCAO system of Gemini[2]), and for future telescopes (e.g. the MCAO system for TMT[3]). A Natural Guide Stars (NGS) implementation[4], thanks to its relative simplicity, would be highly attractive, in particular in view of the recent developments concerning the WaveFront Sensors (WFS) sensitivity[5]; however, the LGS approach has been adopted as baseline for MAORY, as it seems to ensure a better correction uniformity and sky coverage[6].

The current concept of MAORY is characterized by two post-focal Deformable Mirrors (DM) conjugated to the high-altitude turbulent layers, that complement the high-order ground-layer correction and the field stabilization provided by the adaptive telescope, respectively through mirrors M4 and M5. From the wavefront sensing point of view, the MCAO module is characterized by a multiple Sodium LGS WFS for the high-order sensing, using up to 9 LGS as a reasonable

*emiliano.diolaiti@oabo.inaf.it; phone +39 051 2095708; fax +39 051 2095700; www.bo.astro.it

Adaptive Optics Systems, edited by Norbert Hubin, Claire E. Max, Peter L. Wizinowich,
Proc. of SPIE Vol. 7015, 70150U, (2008)
0277-786X/08/$18 · doi: 10.1117/12.789604

limit, and a multiple NGS WFS, to measure the low-order modes, that determines the final sky coverage. In order to re-image the high-altitude layers on the post-focal DMs and to convey the light to the science instruments, a post-focal relay is required, with tight requirements on the optical quality and thermal emissivity. The post-focal relay shall provide two output ports, one with mechanical derotation for a light instrument and another without mechanical derotation for a heavy instrument.

A two years Phase A study for this module is in progress, within the framework of the E-ELT instrumentation studies sponsored by the European Southern Observatory (ESO). The study is performed by a consortium including three observatories of the Istituto Nazionale di AstroFisica (INAF – Osservatorio Astronomico di Bologna, INAF – Osservatorio Astrofisico di Arcetri, INAF – Osservatorio Astronomico di Padova) and by Office National d'Etudes et de Recherches Aerospatiales (ONERA), in collaboration with ESO itself. The study is divided into two phases: Phase 1, dedicated to the requirements analysis and first trade-off studies, and Phase 2, mainly dedicated to the advanced conceptual design. The preliminary results obtained so far are presented in this paper. At the moment of this writing the study is approaching its first important milestone, the Phase 1 review; therefore the concept and the results presented here are not fully consolidated yet.

2. TOP LEVEL REQUIREMENTS

The general top level requirements for MAORY are presented in the following table, including the basic optical, mechanical and thermal specifications.

Table 1. General top level requirements.

Item	**Requirement**
Field of view (diameter)	Large field of view (up to 2') with moderate correction
	Medium field (20" to 1') with high correction
Throughput and wavelength	> 80% for 0.8μm < λ < 2.4 μm (goal 85%)
	> 75% for 0.6 μm < λ < 0.8μm
Thermal background	< 30% thermal background due to the telescope in the K band (goal 15%)
Interfaces to instruments	One port for light instrument (< 4 t) with mechanical derotation
	One port for heavy instrument without mechanical derotation
Maximum dimensions	< 6.5 m × 6.5 m in plant, < 7 m in height

The specific requirements related to the MCAO performance have been derived starting from a global "on-axis" error budget of σ = 200 nm RMS. This figure is inclusive of all possible error sources in the case of a nominally null FoV. The contribution due to the anisoplanatic effects on a non-zero FoV has been then evaluated by means of the generalized isoplanatic angle[7], depending essentially on the Cn^2 profile and on the number of deformable mirrors. Assuming a reasonable turbulence profile, scaled to a seeing FWHM = 0.8" at λ = 0.5 μm at Zenith pointing, and a baseline of 3 DMs, the anisoplanatic error $\sigma=(\theta/\theta_M)^{5/3}$ has been evaluated for different values of FoV. Combining the "on-axis" error budget with the anisoplanatic effects, the following tables of required Strehl Ratio value and uniformity have been derived. In addition to that, requirements on the sky coverage have been defined, specifying the average performance to be achieved over at least 50% of the sky at the Galactic Pole.

Table 2. Top level requirements: average Strehl Ratio across the field of view.

FoV	**λ=2.2μm**	**λ=1.65μm**	**λ=1.25μm**	**λ=0.8μm**
2'	0.43	0.24	0.10	Best effort
1'	0.62	0.43	0.23	Best effort
20"	0.72	0.56	0.37	0.09

Table 3. Top level requirements: Strehl Ratio RMS variation across the field of view.

FoV	λ=2.2μm	λ=1.65μm	λ=1.25μm	λ=0.8μm
2'	0.13	0.13	Best effort	Best effort
1'	0.06	0.07	0.07	Best effort
20"	0.02	0.02	0.02	0.01

Table 4. Top level requirements: average Strehl Ratio across the field of view over at least 50% of the sky at the Galactic Pole.

FoV	λ=2.2μm	λ=1.65μm	λ=1.25μm	λ=0.8μm
1'	0.50	0.30	0.14	Best effort
20"	0.60	0.41	0.23	0.04

The MCAO performance top level requirements are complemented by specifications related to the Point Spread Function (PSF) shape and its spatial and temporal variability. The systematic photometric errors due to the PSF variation across the FoV (neglecting effects like sampling, signal-to-noise ratio) shall be smaller than 3% as a goal. The relative astrometry, specified in terms of the relative position, in different exposures, of a point source with respect to a local reference frame, shall be stable to 1/10 PSF FWHM over a 20" FoV.

3. SYSTEM ANALYSIS AND PERFORMANCE ESTIMATION

The performance analysis and optimization has been performed so far by means of a Fourier code[8], that has proven to be a very effective tool for a preliminary system analysis, essentially thanks to its speed, that allows to span the parameters space in a more efficient way than an end-to-end simulation tool. The Fourier code is based on some assumptions, the most relevant of which is that the pupil is assumed to be of infinite diameter, an approximation that may not be satisfactory in some cases, for instance to account for the LGS cone effect typical of an Extremely Large Telescope. For this reason, a correction term has been implemented in the Fourier code, to account for the unseen part of the turbulence due to the finite aperture and in particular to the cone effect. In the meantime, an end-to-end simulation code is under preparation, to perform a more detailed analysis of the system performance, especially in the Phase 2 of the study.

The first step in the MCAO system analysis has been the evaluation of the effect of the number of DMs and of Guide Stars (GS) on the performance. The analysis of the number of DMs is shown Fig. 1: the performance has been optimized for a 2' diameter FoV for a very high number of GSs, in order to neglect the tomographic error. The performance gain with 2 or 3 DMs with respect to 1 DM is evident. Assuming a baseline of 3 DMs, the sensitivity to the number of GSs (Fig. 2) shows that even a reasonable number of GSs of 5 or 6 ensures a performance definitely better than the required one. Based on these facts, the current concept assumes 3 DMs and 6 LGSs, arranged at the edge of the FoV. A simpler 2 DM option is anyway under investigation for the Phase 1 review.

With the current baseline configuration, a more detailed analysis has been performed, estimating the polychromatic PSFs at different bands (K, H, J, I). These PSFs are going to be used also for the assessment of the photometric and astrometric requirements, at least for the aspects related to the PSF shape and variability across the FoV, while for the effects related to the temporal variability of the atmosphere it will be necessary to perform specific simulations as soon as possible. From the polychromatic PSFs it has been possible to derive Strehl Ratio maps (Fig. 3), always evaluated over the full 2' FoV. The performance assessment made possible by this preliminary analysis is only partial, in that only the generalized fitting error and the tomographic error[6] have been included so far. From the comparison of the expected performance to the required one (see Table 5), it is possible to evaluate the residual error budget, that of course depends also on the target FoV. For a scientific FoV of 45" diameter, corresponding to a square FoV ~30"×30" (relevant for the imager to be fed by MAORY), the residual error budget amounts to $\sigma \approx 160$ nm.

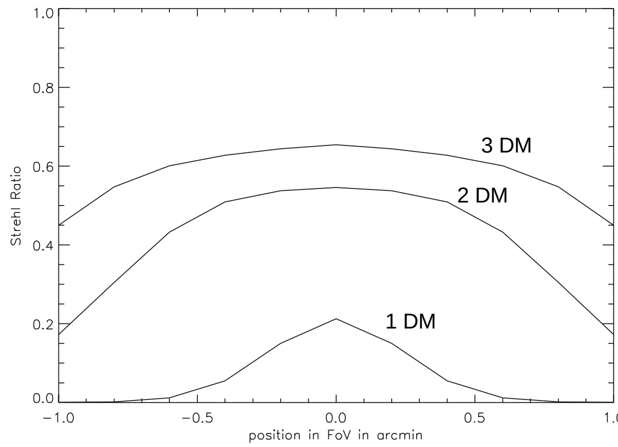

Fig. 1. Performance for 1, 2 and 3 DMs. The performance is optimized for a 2' diameter FoV. A very high number of guide stars is assumed here, in order to have negligible tomographic error.

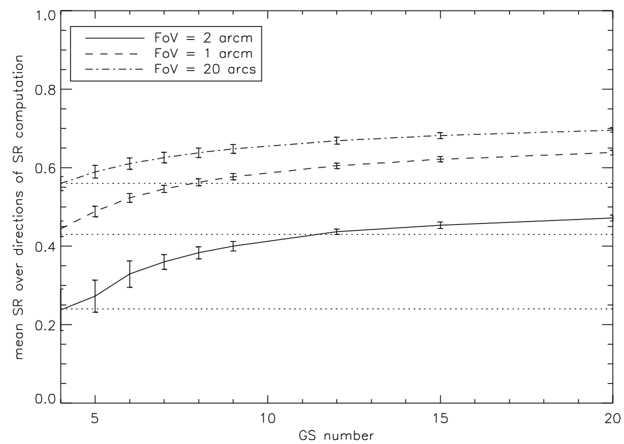

Fig. 2. Average Strehl Ratio across different FoVs (diameter 2', 1', 20'') for a 3 DMs system. The error bars represent the Strehl Ratio variation across the FoV. The dotted horizontal lines represent the required performance.

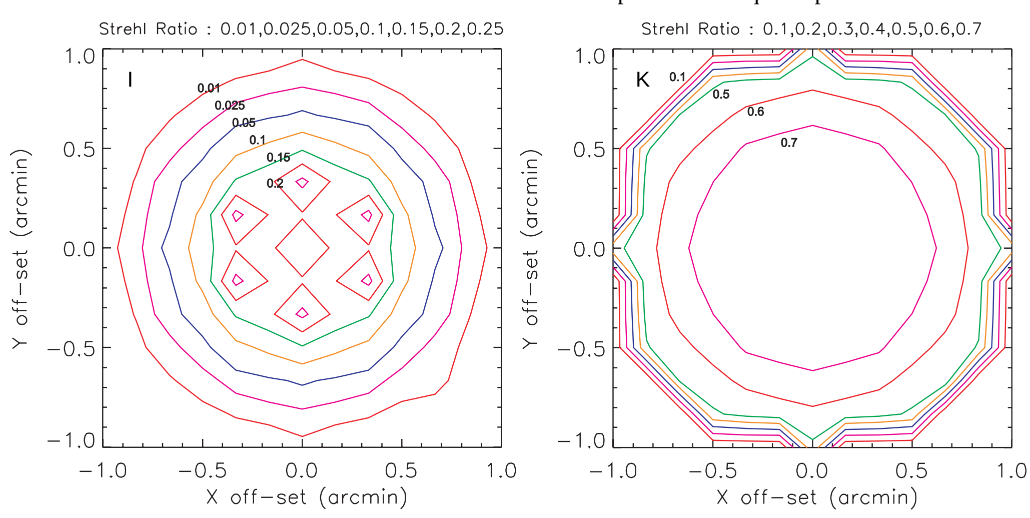

Fig. 3. Strehl Ratio maps, derived by comparing the polychromatic PSFs at two different bands (I, left; K, right) with the corresponding diffraction-limited PSFs. The performance is optimized here over a 45'' diameter FoV, but it is evaluated over the full 2' diameter FoV.

Table 5. Comparison between required and estimated performance. The performance is optimized here for a 45" diameter FoV. The estimated performance includes so far the generalized fitting error and the tomographic error.

	Required Strehl		**Estimated Strehl**	
Band	**mean**	**RMS**	**mean**	**RMS**
K	0.65	0.04	0.81	0.02
H	0.47	0.05	0.68	0.02
J	0.27	0.05	0.52	0.03
I	0.05	0.02	0.22	0.03

4. LGS WAVEFRONT SENSING

LGSs, although potentially very useful to boost the correction and the sky coverage of a MCAO system, present also a number of issues, especially on ELTs. The finite distance of the Sodium layer from the telescope aperture is associated to the so called cone effect, in principle solvable by MCAO. The finite extension of the Sodium layer is responsible for a performance limitation of the conventional WFSs; in the case of a Shack-Hartmann WFS, this finite extension translates into a spot elongation, variable for each sub-aperture, in a way depending on the relative position of the sub-aperture and of the LGS projection point. The spot elongation, in the case of a pulsed laser, can be overcome at least in principle by range gating or dynamic refocus techniques, which by the way pose significant technological problems (see for instance [9] for an interesting implementation). In the case of CW lasers, that currently seem to be more easily available than pulsed lasers, the most straightforward solution is the increase of the laser power and, at the same time, the adoption of an optimized spot position measurement algorithms (weighted center of gravity[10], correlation maximization, matched filtering[11]) to make an efficient use of the available photons. Alternative WFS schemes are also under study[12], although for this conceptual design study higher priority is given to well-assessed schemes.

Assuming a weighted center of gravity algorithm as spot position measurement method, a detailed analysis has been performed of the basic parameters of a Shack-Hartmann WFS, in particular of the spot sampling and sub-aperture size and of the required number of photons per sub-aperture versus the detector read-out noise. This analysis has been performed in the case of LGSs projected from behind the telescope secondary mirror M2 (maximum spot elongation $\theta \approx$ 5" for a $D = 42$ m telescope assuming a Sodium layer of thickness $\Delta H = 10$ km), around the edge of the primary mirror M1 (maximum spot elongation $\theta \approx 10"$) and, finally, assuming no elongation (a situation achievable in principle by range gating or dynamic refocus). The analysis has shown that a good compromise between spot sampling and sub-aperture size is Nyquist sampling (2 pixels per FHWM in the non-elongated axis, corresponding to 0.75"/pixel with a 1.5" intrinsic LGS spot width) and sub-apertures of ~10×10 pixels in the case of center projection and ~20×20 pixels in the case of lateral projection. These parameters ensure relative insensitivity to sampling errors and truncation effects. In order to avoid the contamination between spots in adjacent sub-apertures, a field stop has to be foreseen on the LGS image at the entrance of the WFS. With these assumptions, the required number of detected photons to achieve a target open-loop wavefront error $\sigma = 100$ nm per LGS has been computed. The results of this analysis are presented in Table 6. It should be stressed that the figure of merit adopted here ($\sigma = 100$ nm RMS wavefront error per LGS) does not include any closed loop temporal filtering or tomographic averaging of multiple LGS signals, so it might be unnecessarily stringent. A more detailed discussion is presented in [8].

Table 6. Number of detected photons required to achieve an open-loop RMS wavefront error σ=100nm per LGS. Three situations are considered: LGS projected from behind M2, from the edge of M1 and, finally, no spot elongation, that could be achieved with a pulsed laser by range gating or dynamic refocus.

RON	**LGS from behind M2**	**LGS from edge M1**	**No elongation**
1 e^-	1251	3080	300
3 e^-	1483	3290	460
5 e^-	1734	3537	580

Another relevant aspect to be considered is the Rayleigh scattering of the LGS light in the lower atmosphere and the corresponding "fratricide" effect among different LGSs. A sketch of this effect on one out of six LGSs, projected from behind M2, is presented in Fig. 4, showing that approximately 10% of the total number of sub-apertures are significantly affected by a relevant background contamination and related noise. This effect practically disappears in the case of lateral projection of the LGSs, although in this case the spot elongation is doubled. The way to handle this problem and the sub-apertures contamination is under investigation.

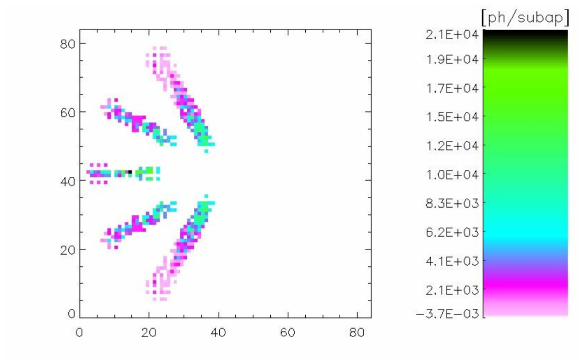

Fig. 4. Rayleigh scattering effects. Assuming a constellation of 6 LGS, the five "plumes" represent the scattering of 5 LGS onto the 6th LGS. The flux is normalized in such a way that the average number of photons per sub-aperture from the LGS of interest is N_{ph} = 900.

5. NGS WFS AND SKY COVERAGE

As all the LGS-based systems, MAORY requires a tip-tilt measurement, for instance from one or more NGSs. In order to avoid tilt anisoplanatism problems[6], at least 3 tip-tilt NGS are required. One of these NGSs is probably used also to measure the defocus term: in principle, the defocus can be retrieved by the LGS signal, but the rapid and somewhat unpredictable variability of the Sodium layer centroid makes the defocus measurement performed by the LGSs only of little use (see also Section 6). An independent measurement of the defocus by means of a NGS, complemented by the LGS tomography of the defocus across the FoV, may be a suitable solution to the problem.

In order to have a first assessment of the required NGS magnitude, a preliminary analysis has been performed for the tip-tilt measurement only, assuming a simple spot position measurement algorithm (centroid with windowing). A target tip-tilt estimation error of 2 mas RMS has been adopted corresponding to a RMS tip-tilt wavefront error σ = 100 nm. This figure of merit is essentially the same adopted for the LGS WFS noise and is of course preliminary. Moreover it does not include the noise reduction ensured by the combination of multiple NGS signals and the closed loop filtering effect.

Table 7. Parameters for evaluation of limiting magnitude of NGS WFS. Centroid of star image evaluated by center of gravity with windowing.

Parameter	**Value**
Spot FWHM	8 mas
Pixel size	4 mas
Centroid window	16 mas
RON	0, 5, 10, 15, 20 e^-
Background	14.4 mag/arcsec^2
Strehl Ratio	0.1, 0.2
Total efficiency	0.4
Integration time	10 ms

With these approximations, it has been verified that a tip-tilt measurement in a visible band (e.g. R) requires too bright NGS (R~14). Much more encouraging results have been obtained performing the tip-tilt measurement in the near-infrared, e.g. in the H band[3], where the MCAO system delivers a good correction level over the FoV. This approach is based on some important assumptions: the high-order loop has to be closed by the LGS WFS only; the sky background rejection, e.g. by windowing the shrunk NGS spot image, is crucial; the correction level over the NGS search field is essential. With the parameters listed in Table 7, a preliminary analysis of the tip-tilt error versus the H band NGS magnitude has been performed (Fig. 5). With a Strehl Ratio of 0.2, the required NGS magnitude is around H=19.

In order to translate this figure into a sky coverage estimate, a search FoV for the NGSs has to be defined. This depends on a number of aspects, including tilt anisoplanatism effects and interface issues with the scientific instruments. While it is possible in principle to share the corrected FoV with the instrument by means of wavelength-splitting dichroics, the better solution in terms of opto-mechanical complexity seems to be a spatial splitting of the output FoV. The unvignetted FoV required by the instruments has not been defined yet. Assuming a 1'×1' unvignetted FoV, the NGS search field corresponds to the outer complementary part, out to the 2' external diameter, corresponding to a search area of approximately 2 $arcmin^2$. From the star counts shown in Fig. 6, derived from the Besançon model and verified on some Sloan Digital Sky Survey data, one may expect on average at least 4 NGS per search field at low Galactic latitudes (b<30°) and at least 1.5 NGS per search field at b = 90°. Considering the properties of a Poisson distribution, the probability to have at least 3 NGS per search field is then respectively P~80% at low Galactic latitudes and P~20% at high Galactic latitudes. These simple considerations cannot be considered a real sky coverage estimate, but at least they give a first positive indication.

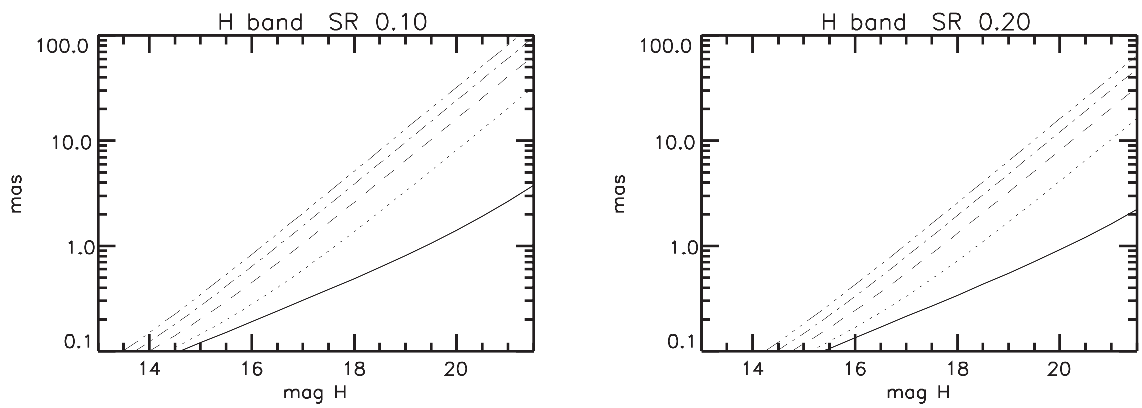

Fig. 5. NGS tip-tilt error as a function of H band magnitude for two different cases of Strehl Ratio: 0.1 (left) and 0.2 (right).

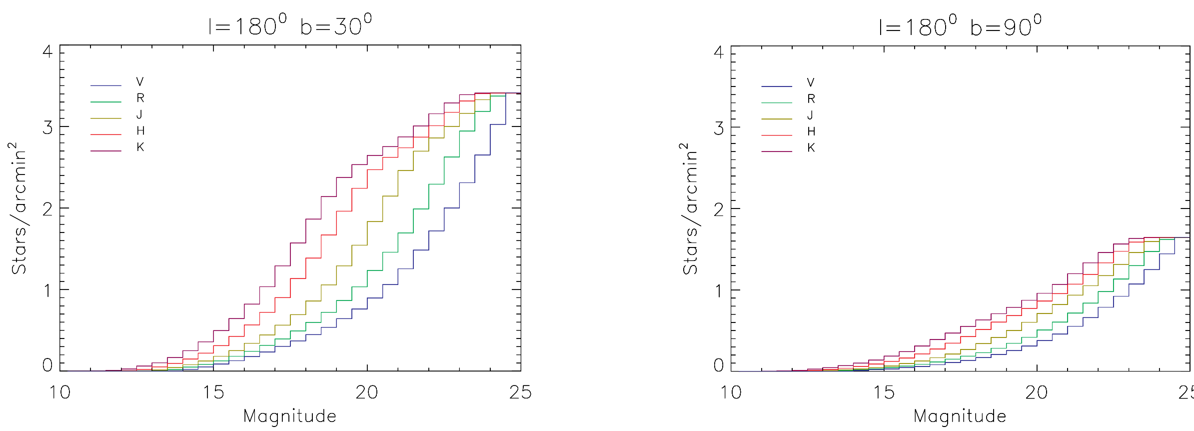

Fig. 6. Cumulated star counts per $arcmin^2$ for different bands, derived from the Besançon model at two different Galactic latitudes b (left: close to the Galactic plane; right: at the Galactic Pole).

6. OPTICAL DESIGN AND DESIGN ISSUES

Different optical design concepts have been analyzed and are under investigation[13]. One of the simplest solutions might have been an off-axis parabolas scheme, with the DMs in the collimated beam between the two off-axis parabolas. This solution, however, has been found to be unfeasible due to space constraints in the collimated beam, related also to the post-focal DMs minimum size, that is defined by the number of actuators across the diameter and by the inter-actuator pitch. An alternative design is shown in Fig. 7: it is based on a double Offner-type relay. The intermediate mirrors of the two Offner-like relays (M8 and M13) are the two post-focal DMs. Excluding the dichroic required at the output of the post-focal relay for the LGS/science FoV splitting and assuming an efficiency of ~97% per reflection, the total throughput of this design is ~78%. The optical quality is very good (Fig. 8). Some aspects remain to be investigated, like the clearance in the region of the output focal plane, where important units have to be located, including the above mentioned dichroic, but also a mechanical derotator for a light instrument and, very likely, the NGS WFS probes. However, this seems to be an interesting design.

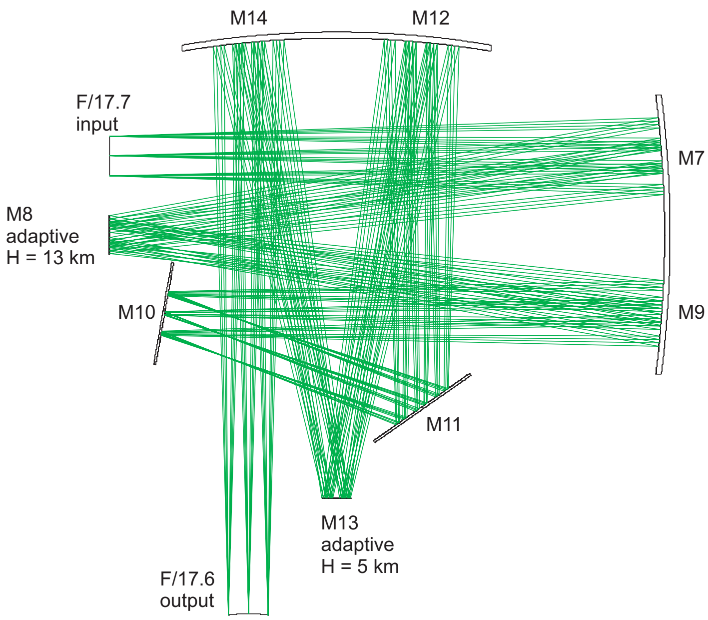

Fig. 7. A possible post-focal relay optical design, The FoV shown here is 2' diameter. Some mirrors are oversized to account for the LGS light. The LGS technical FoV is assumed here to be 216" diameter.

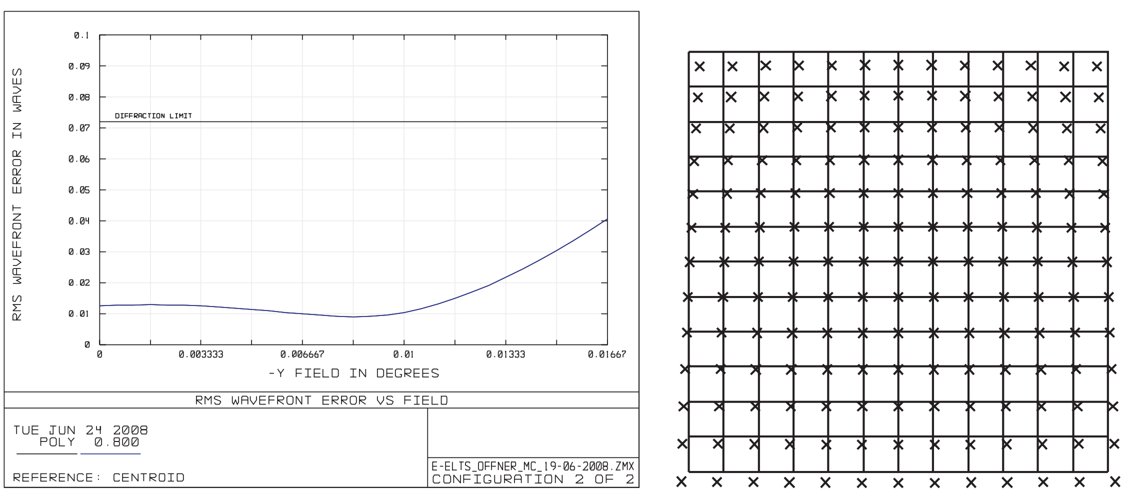

Fig. 8. Left: RMS wavefront error in wavelength units (λ = 0.8 μm) vs. field position. The horizontal line is the diffraction limit. Right: geometric distortion pattern, magnified by 10×; the maximum distortion at the field edge is < 0.07%.

The optical design presented before accounts for a known problem related to the use of LGSs: the required FoV to let the LGS light pass through is larger than the science FoV (Fig. 9 and reference [6]). One may also reduce the off-axis angle of the LGSs, although a part of the atmospheric volume covered by the science FoV would not be sampled by the LGS. A detailed analysis is in progress, to quantity the loss of performance when narrowing the LGS technical FoV.

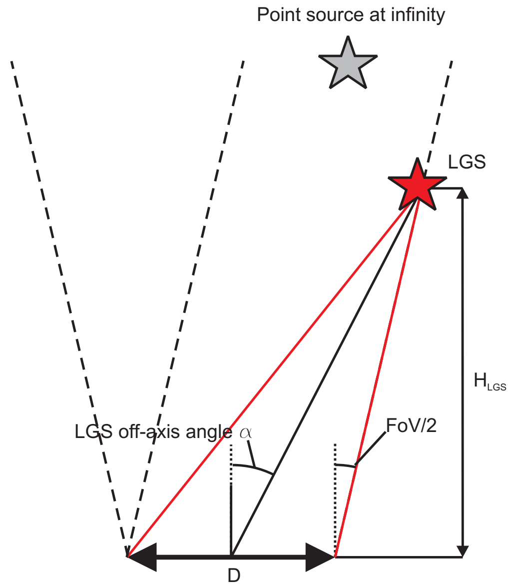

Fig. 9. LGS technical field of view illustration. Given a point source at infinity, located at the edge of the scientific FoV, the LGS off-axis angle α required to sample the full atmospheric volume corresponding to the science FoV is bigger than the off-axis angle of the point source at infinity.

The LGS focus on an ELT is very sensitive to the Sodium layer centroid, that changes in a predictable way with the Zenith angle during the observation but also in a random way due to the intrinsic variability of the Sodium layer. The sensitivity to a 100 m offset of the Sodium centroid is shown in Table 8. The effect is huge and suggests that a defocus measurement by a NGS is required, as previously anticipated.

Table 8. Defocus due to a shift of the Sodium layer centroid by ΔH = 100 m when the centroid range is initially at range H.

Range H	**Defocus for ΔH = 100 m**
84 km	880 nm
100 km	650 nm
180 km	180 nm

Table 9. Aberration coefficients at LGS image plane after the post-focal relay when the Sodium layer focus offset vs Zenith angle is compensated. LGS off-axis angle α = 108".

Zenith angle	**0°**	**30°**	**60°**
Astigmatism	7068 nm	5419 nm	2356 nm
Coma	1590 nm	1296 nm	825 nm
3rd order Spherical	177 nm	118 nm	59 nm

Even when the LGS WFS is kept in focus, other Zenith-dependent low-order aberrations affect its performance (Table 9). Clearly these aberrations have not to be corrected for by the DMs. After a preliminary analysis, an effective way to measure these low-order aberrations seems to be a temporal filtering of the LGS WFS signal. In the worst case, i.e. at a Zenith angle z = 60°, the astigmatism coefficient shown in Table 9 changes by ~50 nm in Δz ~ 0.55°, corresponding to Δt ~ 120 s: this interval is probably long enough to allow the estimation from the LGS signal of the Zenith-dependent astigmatism, without being affected by the atmospheric contribution to the same mode. In any case, additional information can also be provided by look-up tables and a proper calibration of these Zenith-dependent low-order aberrations. Different options are under investigation to handle these low-orders, once they are known. A possibility is to treat them as a simple slope offset or, if the dynamic range of the LGS WFS is compromised, they can be corrected in real-time by means of a dedicated high-stroke low temporal rate DM in the non-common path of the LGS re-imaging optics.

Another issue currently under investigation is related to the pupil rotation. Due to the elevation movement of the telescope, M4 and M5 (respectively the telescope high-order and tip-tilt mirrors) rotate with respect to the post-focal DMs located on the Nasmyth platform. In addition to this, the LGS constellation, in the case of center projection, may be kept fixed with respect to the sky (and hence to the NGSs) or to the telescope. In the former case, assuming that the LGS WFS tracks the LGSs on the image plane, all DMs rotate with respect to the LGS WFS, at different speeds. It has been estimated that, assuming a minimum Zenith angle z = 5°, the LGS WFS pupil rotates with respect to the DMs at a speed corresponding to a shift of 1/10 sub-aperture at the pupil edge in ~3 s, a time that decreases very quickly with the Zenith angle. If the LGS constellation is kept fixed with respect to the telescope, the M4 rotation with respect to the LGS WFS pupil is frozen; the maximum rotation speed in this case is that of the post-focal DMs, corresponding to a shift of 1/10 sub-aperture every ~30 s for a Zenith angle z = 5°. The possibility to compensate these rotation effects by an optical derotator has been considered: the size, weight and requirements of this device, however, make it very difficult to realize in practice. For this reason a software derotation of the pupils and meta-pupils, at the level of the control matrices, is now under investigation.

REFERENCES

[1] Gilmozzi, R., "The European Extremely Large Telescope", Proc. SPIE 7012, this Symposium.

[2] Ellerbroek, B., L., Rigaut, F., J., Bauman, B., J., Boyer, C., Browne, S., L., Buchroeder, R., A., Catone, J., W., Clark, P., d'Orgeville, C., Gavel, D., T., Herriot, G., Hunten, M., R., James, E., Kibblewhite, E., J., McKinnie, I., T., Murray, J., T., Rabaud, D., Saddlemyer, L., K., Sebag, J., Stillburn, J., Telle, J., M., Veran, J.-P., "Multiconjugate adaptive optics for Gemini-South", Proc. SPIE 4839, 55-66 (2003).

[3] Herriot, G., Hickson, P., Ellerbroek, B., L., Andersen, D., A., Davidge, T., Erickson, D., A., Powell, I., P., Clare, R., Gilles, L., Boyer, C., Smith, M., Saddlemyer, L., Véran, J.-P., "NFIRAOS: TMT narrow field, near-infrared facility adaptive optics", Proc. SPIE 6272, 62720Q (2006).

[4] Ragazzoni, R., Farinato, J., Marchetti, E., "Adaptive optics for 100m class telescopes: new challenges require new solutions", Proc. SPIE 4007, 1076-1087 (2000).

[5] Guyon, O., Blain, C., Takami, H., Hayano, Y., Hattori, M., Watanabe, M., "Improving the Sensitivity of Astronomical Curvature Wavefront Sensor Using Dual-Stroke Curvature", Publications of the Astronomical Society of the Pacific 120, 655-664 (2008).

[6] Rigaut, F., J., Ellerbroek, B., L., Flicker, R., "Principles, limitations and performance of multi-conjugate adaptive optics", Proc. SPIE 4007, 432-441 (2000).

[7] Tokovinin, A., Le Louarn, M., Sarazin, M., "Isoplanatism in a multiconjugate adaptive optics system", J. Opt. Soc. Am. A 17, 1819-1827 (2000).

[8] Conan, J.-M., Petit, C., Robert, C., Fusco, T., Neichel, B., Diolaiti, E., Foppiani, I., Schreiber, L., Esposito, S., Marchetti, E., "E-ELT MCAO module performance estimation and optimisation", Proc. SPIE 7015, this Symposium.

[9] Baranec, C., J., Bauman, B., J., Lloyd-Hart, M., "Concept for a laser guide beacon Shack-Hartmann wave-front sensor with dynamically steered subapertures", Optics Letters 30, 693-695 (2005).

[10] Nicolle, M., Fusco, T., Rousset, G., Michau, V., "Improvement of Shack-Hartmann wave-front sensor measurement for extreme adaptive optics", Optics Letters 29, 2743-2745 (2004).

[11] Gilles, L., Ellerbroek, B., L., "Shack-Hartmann wavefront sensing with elongated sodium laser beacons: centroiding versus matched filtering", Applied Optics 45, 6568-6576 (2006).
[12] Schreiber, L., Lombini, M., Foppiani, I., Diolaiti, E., Conan, J.-M., Marchetti, E., "An optical solution to the LGS spot elongation problem", Proc. SPIE 7015, this Symposium.
[13] Lombini, M., Diolaiti, E., Foppiani, I., Schreiber, L., Marchetti, E., Delabre, B., "Preliminary design of the post focal relay of the MCAO module for the E-ELT", Proc. SPIE 7015, this Symposium.